ORIGIN OF HI-TI LUNAR ULTRAMAFIC GLASSES: EVIDENCE FROM PHASE RELATIONS AND DISSOLUTION KINETICS OF HIGH-TI MAGMA OCEAN CUMULATES. T. L. Grove[1] and J. Van Orman.[1], Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139 tlgrove@mit.edu.

Introduction Lunar ultramafic glasses vary widely in their Ti content from 0.26 to 16.4 wt. % TiO_2. Many models have been proposed to explain this compositional variation and each has important consequences for the evolution of the lunar interior. Ringwood and Kesson [1,2] explored a variety of models that called upon the sinking of dense cumulate residues produced during the crystallization of a 300 km deep magma ocean at 4.6 to 4.4 AE. The magma ocean cumulates sank into underlying primordial mantle, and were remelted to form the picritic mare basalt magma at 400 to 500 km depth by the late heating (starting at 3.8 AE) and melting of the deep interior. Another model for the origin of the compositional variation observed in lunar ultramafic glasses calls on assimilation of magma ocean cumulates at shallow depths by a low-Ti ultramafic parent that has risen from great depth in the lunar interior. This assimilation model was proposed by Hubbard and Minear [3] but was rejected by Ringwood and Kesson [1]. Wagner and Grove [4] have revived the shallow assimilation model because: 1) it can account for the geochemical signatures of ultramafic glasses, 2) it provides a mechanism whereby the heat necessary for assimilation of cumulates can be provided by a primitive, hot magma generated at depth and it 3) does not require reshuffling of cumulates over large vertical distances in the moon. Furthermore, the melt from a deep hybridized source will sink, rather than rise, because it is denser than its surroundings at the pressure of melt production indicated by its multiple saturation point [5,6].

This abstract describes experimental investigations designed to test an assimilation model for the origin of the high-Ti ultramafic glasses that leaves the dense, TiO_2-rich cumulates in their initial stratigraphic position near the top of the cumulate pile beneath the lunar crust. Wagner and Grove [4] measured the dissolution rates of ilmenite in synthetic analogs of lunar low-Ti and high-Ti ultramafic glass compositions at temperature and pressure conditions similar to those present in the magma ocean cumulate postulated to be present in the lunar upper mantle. Ilmenite dissolves incongruently to chrome-rich spinel and a high-Ti liquid and the reaction proceeds rapidly by a diffusion-controlled mechanism. The dissolution rates for ilmenite are significantly faster than those measured for pyroxenes (Brearely and Scarfe [7] and Zhang et al. [8]) and these differences support a shallow assimilation origin for the high-Ti cumulates. However, the rates of dissolution for a mineral in a melt depend on the compositions of the solid and melt and the degree of supersaturation for the mineral in the melt [9]. If the mineral is saturated (in equilibrium) the driving force for dissolution will be low. As the two phases depart from an equilibrium condition, the driving force for dissolution increases. Hence, realistic assessments of dissolution rates require quantitative information on the temperature and pressure of the process, the compositions of the phases that are dissolving and the degree of supersaturation for each phase. The experiments described here are a first step for providing this quantitative information for magma ocean assimilation processes.

Phase Equilibrium Experiments A synthetic analog of a calculated lunar magma ocean cumulate [10] was prepared and the phase relation were determined at 0.1 MPa and 1 GPa. The composition was selected to be an average of the upper part of the magma ocean cumulate where pigeonite, high-Ca clinopyroxene and ilmenite are cumulus phases. The composition is extremely mafic with FeO + MgO = 39 wt. %, Mg# = 0.34, TiO_2 = 8.7 %, Al_2O_3 = 2.9 % and CaO = 8.7 %. The liquidus for this composition is ~ 1150 °C at 0.1 MPa. At 1125 °C, pigeonite, hi-Ca pyroxene and ilmenite are crystallizing phases. An experiment at 1050 °C, 0.1 MPa shows < 10 % residual liquid. The slope of the liquidus (dP/dT) is ~ 0.07 °C/ MPa. In contrast, the liquidus of a primitive low Ti Apollo 15 green glass [11] is 1410 °C at 0.1 MPa and the slope of the liquidus is 0.04 °C/ MPa. Thus, an important first order constraint on assimilation rates is that all phases in a shallow magma ocean cumulate will be far from the liquidus temperature for their bulk composition, when they are in contact with a hot primitive ultramafic low-Ti magma. The cumulate will be at superliquidus conditions and superheat will be on the order of 300 °C. Dissolution rates for these cumulates are expected to be fast for all mineral phases.

Dissolution rate experiments A polycrystalline aggregate of the high-Ti magma ocean cumulate was fabricated at near-solidus conditions and used as starting material for a series of dissolution rate experiments. The synthetic oxide mix was held above the solidus, but below the liquidus for two hours, then cooled to solidus conditions and allowed to equilibrate for 24 hours. The grain size in the resulting synthetic cumulate varied from 100 to 500 microns. This synthetic cumulate was used as starting material for experiments that examine the dissolution rate of a polycrystalline analog of a shallow-level, high-Ti, magma ocean cumulate. The geometry of the dissolution experiment is similar to that utilized by [4]. A dissolution experiment carried out at 1450 °C for 600 seconds showed an extent of reaction/dissolution for the pyroxene-bearing fine-grained high-Ti cumulate that is greater than that observed for single crystals of ilmenite that were dissolved under identical conditions by [4]. Hence, dissolution rates of iron-rich pyroxenes that coexist with ilmenite in high-Ti cumulates are fast at large departures from equilibrium. Potentially, these pyroxene dissolve at rates as rapid as those determined by [4] for ilmenite dissolution.

Implications The rapid dissolution rates inferred for iron-rich, low-Ca and high-Ca pyroxenes have implications for models of mare basalt and lunar ultramafic glass genesis.

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There is the potential that most lunar mare magmas have experienced significant interaction with shallower mantle upon their ascent from deep mare source regions. The ultimate origin of lunar mare basalts remains a challenge for petrologists. Longhi [12] has shown that high pressure multiple saturation boundaries >2.5 GPa are relevant for low-Ti ultramafic magma genesis. The melting processes involve olivine + low-Ca pyroxene + garnet and depths of origin may exceed 500 km. These magmas will encounter a significant column of lunar mantle prior to eruption on the moon's surface. Therefore, assimilation of lunar mantle may be an importance process in the generation of lunar ultramafic glasses and mare basalts.

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